THE NUCLEAR REACTOR AS A RESEARCH INSTRUMENT

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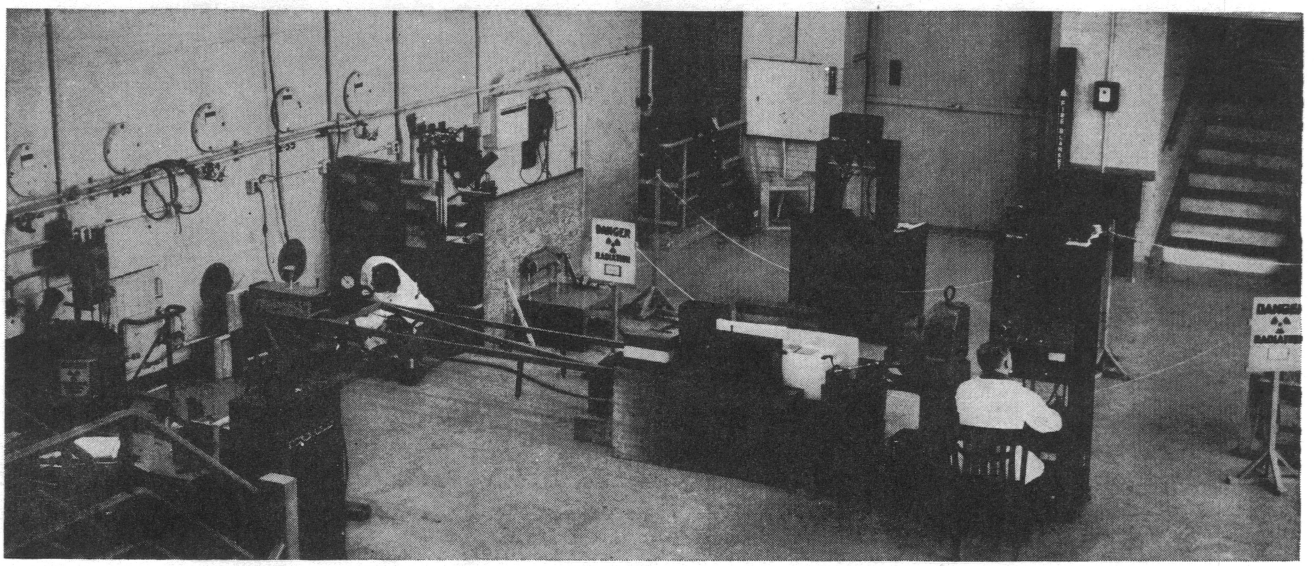
The Nuclear Reactor as a Research Instrument

The blizzard of neutrons in an atomic pile may be channeled to probe the nature of matter. Their application in ingenious experiments makes important contributions to basic physics

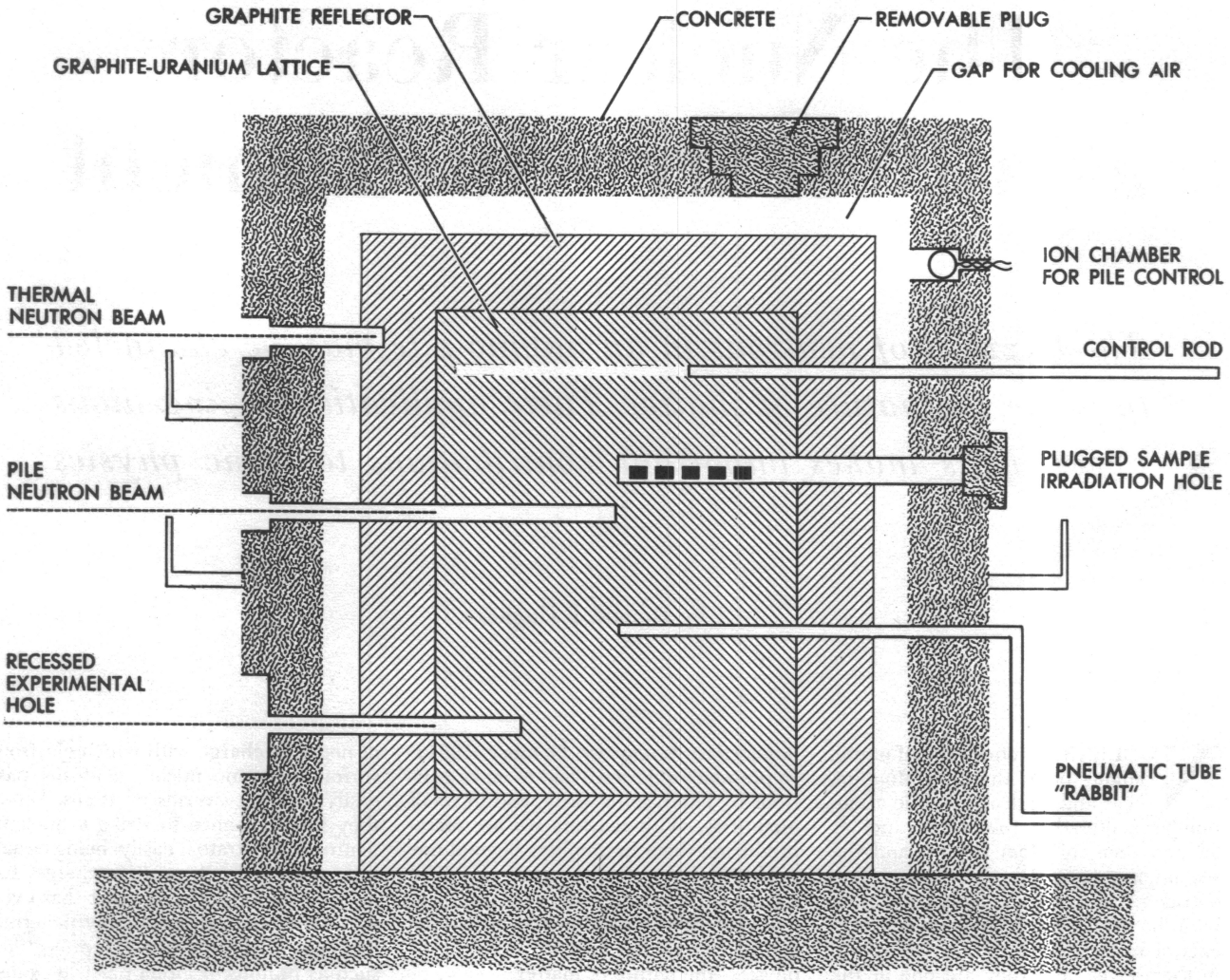
by Donald J. Hughes

NUCLEAR reactors manufacture, among other things, plutonium, heat and neutrons. Public attention has centered on the first product, as an ingredient of atom bombs, and the second, as a potential power source. Scientists are almost exclusively concerned with the third. As fundamental constituents of matter, neutrons are interesting in themselves, and they are one of the most powerful tools in the kit of the experimental physicist [see "The Neutron," by Philip and Emily Morrison; SCIENTIFIC AMERICAN, October, 1951] In pre-reactor days we had to make neutrons by hand, so to speak, and in small quantities. With reactors we are mass-producing them in numbers beyond our wildest dreams of a few years ago. The torrent of neutrons now available provides us with an ideal means of investigating one of the central problems of physics—the nature of matter.

Why are neutrons so effective as probes of matter? First, they have no electric charge. Unaffected by the clouds of negative charge with which electrons surround atomic nuclei, neutrons pass easily through swarms of atoms. When they finally chance to strike a nucleus, neutrons penetrate it easily, being equally unaffected by its positive charge. Especially important is the fact that even very slow neutrons are highly penetrating. All other experimental projectiles, such as protons or alpha particles, must move so fast to get into the nucleus of the atom that they cannot be used to investigate the intricate details of its



REACTOR at Brookhaven National Laboratory is used solely for experimental purposes. The shield of the reactor is at the left; it is pierced with holes that emit neutrons. Here most of the holes are plugged, but one is open for a neutron-reflection experiment. The neutron "mirror" is at the left end of the long apparatus.



CROSS SECTION of the Brookhaven reactor shows its experimental features in simplified form. The uranium fuel of the reactor is embedded in a graphite moderator, which is surrounded by a graphite reflector, which is surrounded by a concrete shield. The moderator and reflector are pierced with holes that emit the neutrons.

HOLE extending into the center of the Brookhaven reactor is a foot square and 20 feet deep. At the far end of the hole may be seen an arrangement of bismuth blocks. The neutrons that emerge from this hole are utilized in experiments involving the "fast chopper" (*see illustrations at the bottom of the opposite page*).

structure. Such details can only be observed with slow neutrons of accurately controlled velocity.

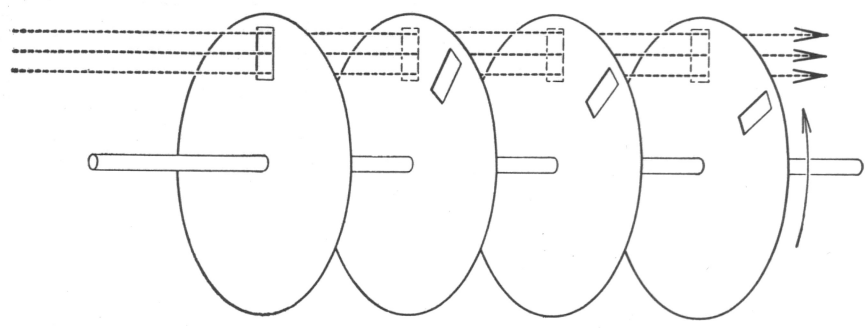
Second, the neutron is magnetized. Thus it reacts with the magnetic fields of atoms, yielding valuable information about magnetic properties. Finally, the neutron is a wave; or rather, like all bits of matter, it is both particle and wave. Some of the most informative experiments we can perform are based on the wavelike interaction of neutrons with matter. Only the intense beams that reactors provide make it possible to take practical advantage of the wave nature of neutrons.

THE very quality that makes neutrons so valuable as an experimental probe makes them hard to utilize. Charged particles are docile beasts. We can speed them up or slow them down with electric fields, steer and aim them with magnets. The uncharged neutrons, however, are unaffected by these forces and are difficult to maneuver. Even to know where they are is something of a problem since they do not announce themselves directly by leaving ion trails in cloud chambers or photographic emulsions as charged particles do. Before neutrons could be put to use a great deal of experimental ingenuity went into learning how to manipulate them.

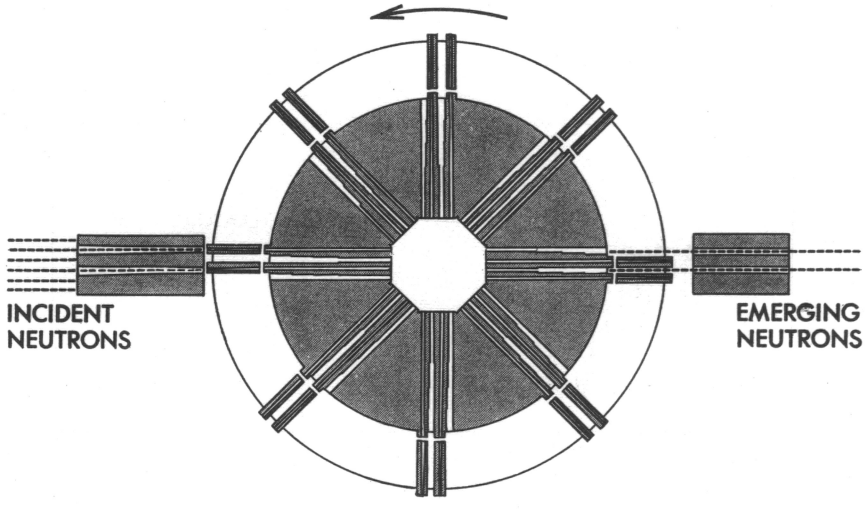
Experimenting with neutrons means, in essence, exposing a piece of material to them and observing how they are affected. Some may be absorbed, others deflected from their original path. The "cross section" of various atomic nuclei for absorbing or scattering neutrons (*i.e.*, the probability that the atom will absorb or scatter a neutron that hits it) tells us a good deal about the atoms and about the neutrons themselves.

A direct and comparatively simple way to use reactor neutrons for cross-section measurements is to put the material being studied inside the reactor. Despite their great size, reactors are extremely sensitive to changes in the number of neutrons available to maintain their chain reaction. An accurate measure of the availability of neutrons in the reactor can be obtained by noting how far the reactor's control rod must be pulled out in order to get the chain reaction started. When even a tiny sample of foreign, neutron-absorbing material is inserted in the reactor, the control rod will have to be pulled out measurably farther than normally. The extra distance measures the neutron absorption of the sample and hence its cross section. Another way to get this result is with the "pile oscillator." Here the sample is moved in and out of the reactor at a steady rate so that its power level rises and falls.

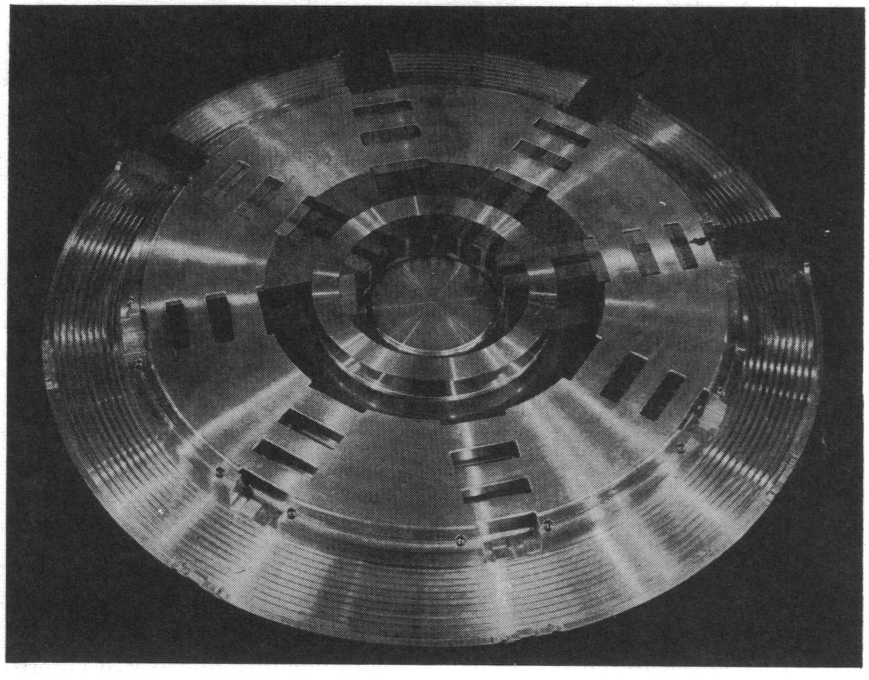
IN THESE experiments the reactor is itself a measuring instrument. For most work, however, it serves merely as



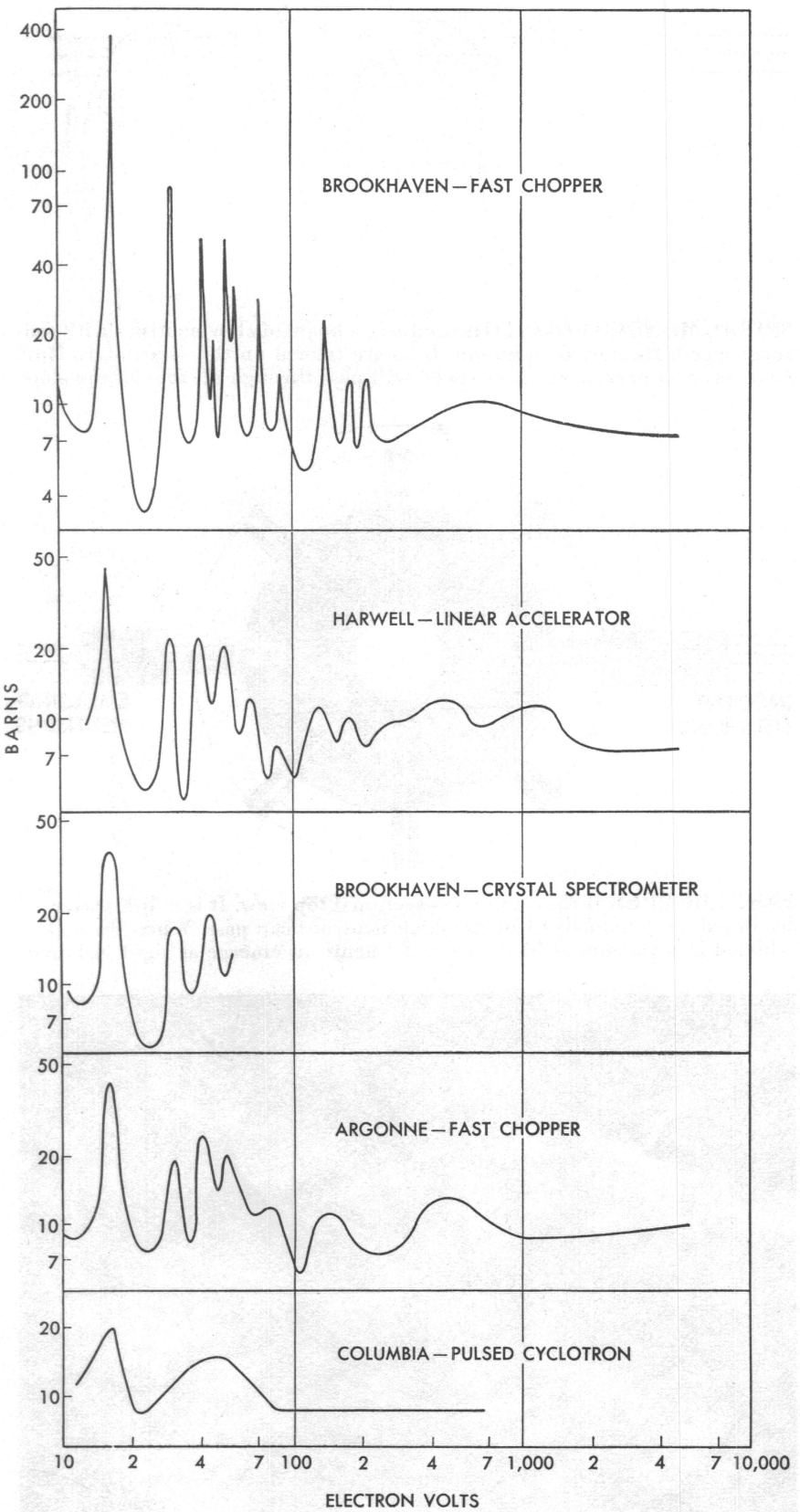
SPIRAL MONOCHROMATOR produces a beam of slow neutrons with uniform speed. Its slotted cadmium disks are turned on the same shaft. Only neutrons of a narrow range of speed will pass through all four of the slots.



FAST CHOPPER is shown in cross-sectional top view. It is a disk traversed by 16 pairs of channels through which neutrons can pass. When the disk is whirled in a vacuum at high speed, the neutrons emerge at right in bursts.



ROTOR of the chopper is made of forged aluminum with plastic inserts which form the channels through which the neutrons pass. When the rotor is spun at full speed, it is able to chop 1,000 bursts of neutrons per second.



HIGH RESOLUTION of the Brookhaven fast chopper in the measurement of nuclear "cross sections" is illustrated by these curves. The cross section of the nucleus, measured in "barns," is the probability that it will absorb a bombarding particle. Each curve represents the cross section of the silver nucleus when bombarded with neutrons of various energies, measured in electron volts. Because the Brookhaven chopper produces neutrons of precisely known energy, it is able to reveal cross sections in unusually fine detail.

a neutron source. Neutrons are brought out of the pile through holes running from the interior out through the shield. The beam that pours out of the experimental holes contains enormous numbers of particles in a wide range of energies. The fastest, coming directly from fissioning uranium atoms, have energies as high as 10 million electron volts. The slowest, those that have lost almost all of their energy in passing through the graphite (or, in the case of some reactors, heavy water) moderator, have an energy of only .0001 electron volt. Thus the fastest neutrons are some 100 billion times more energetic than the slowest. Each particle, it must be remembered, is also a wave. The formula for particle wavelength tells us that it varies inversely with speed. The fastest neutrons in the beam have wavelengths of a few hundred-thousandths of an angstrom unit, even shorter than the diameter of an atomic nucleus (an angstrom unit is a hundred-millionth of a centimeter). The slowest neutrons, on the other hand, have a wavelength of 30 angstrom units, far longer than the distances between atoms in crystals.

In different sections of this broad energy spectrum the neutrons have wholly different properties, both as to the way they must be manipulated and as to their effects on matter. High-energy neutrons behave like solid pellets; slow neutrons lose their particle character almost entirely and act like almost pure waves. The principal task of the reactor experimenter is to sort neutrons of various speeds and to observe how particles of each speed interact with matter.

THE NEUTRON beam divides into three main speed ranges. The so-called fast neutrons are those with energies extending from 10 million down to about 10,000 electron volts. Below these in the hierarchy of energies are "resonance" neutrons, from 10,000 electron volts to .01 electron volt. Finally there are the thermal neutrons, with energies from .01 to .0001 electron volt.

In many experiments we do not try physically to separate the various particles from one another. Instead we use detecting devices that respond only to the type of neutron we are studying. Thus fast neutrons make themselves known by knocking protons out of a detecting substance such as paraffin. In cloud chambers the protons produce ion trails from which we can deduce the energy of the particles, and hence the energy of the neutrons that produced them. Counting the proton tracks of a particular energy tells us how many neutrons of corresponding energy are in the beam. Suppose we want to measure the cross section of gold for million-volt neutrons. First we expose the detector to the reactor beam and count only the million-volt neutrons. Then we put a

thin gold foil into the beam and note the decrease in these particles, which represents the number of million-volt neutrons removed by the gold. Most basic research in the fast range deals with nuclear cross sections, either for absorption or scattering.

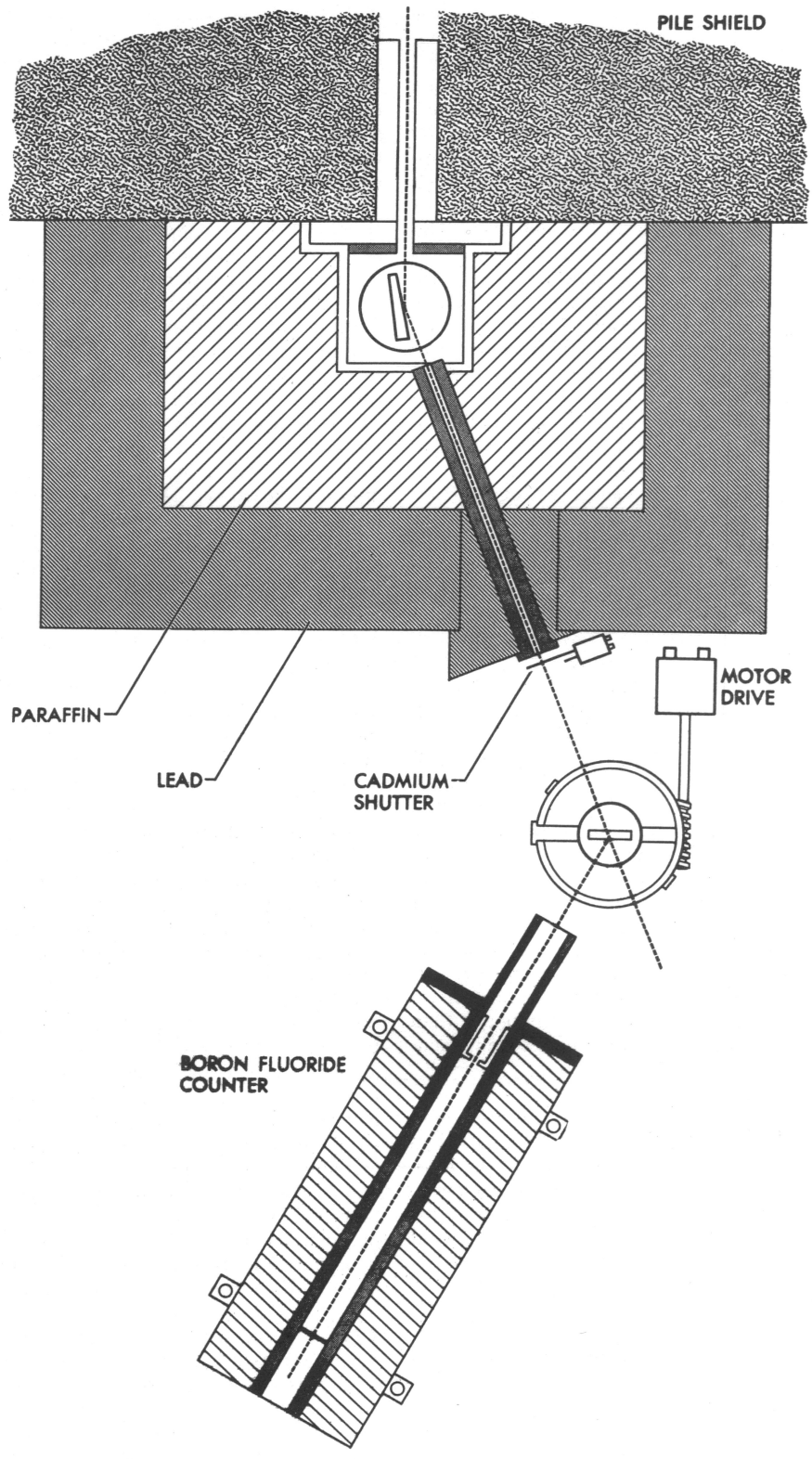
RESONANCE neutrons are a kind of mixed breed. The faster ones must be handled like particles, but their effects depend on their wave nature. Having wavelengths of about the same size as nuclear diameters, they interact with nuclei in a wavelike manner. At certain wavelengths they resonate with a nucleus, which means they are strongly absorbed; at slightly different wavelengths they are "out of tune" and their absorption greatly decreases. The neutron absorption curve of a particular nucleus thus shows sharply separated peaks at isolated wavelengths.

Nuclear physicists are very interested in these curves because they promise to throw light on one of the murkiest problems now facing us—the internal structure of the nucleus [see "The Structure of the Nucleus," by Maria G. Mayer; SCIENTIFIC AMERICAN, March, 1951]. Is it formless, like a liquid drop, or does it have a "shell" structure? The shell theory states that neutrons and protons occupy fixed orbits or shells in the nucleus, much as the electrons do outside it. A nucleus whose outermost shell is completely filled should be very stable. The numbers of neutrons and protons required to fill successive shells are known as the "magic numbers."

Neutron absorption experiments give some strong evidence for the shell model. One of the magic numbers is 50, and tin contains 50 protons. When we compare the absorption spectrum of tin with that of silver, we can see that tin is indeed unreactive. Whereas the silver nucleus finds many neutron energies that excite it, tin is apparently satisfied with its make-up and rejects all neutrons indifferently.

BUT we are still far from having a satisfactory theory of the nucleus. We need much more information on the activity and energy levels of various nuclei, and neutron absorption experiments are one of the best ways to get it. It is essential to find out just which energies are absorbed by each nucleus, and which rejected. This means that we must be able to distinguish sharply between neutrons of different speeds. The sharper our separation, the greater the resolving power of our nuclear spectroscope, and the less the chance that what appears to be a single absorption peak is really two or more separate ones.

The device with which we are now getting the sharpest separations is the "fast chopper," recently developed by F. G. Seidl at the Brookhaven National



NEUTRON DIFFRACTION experiments at Oak Ridge National Laboratory employ the arrangement depicted in this top view. The neutrons emerge from the reactor at the top. They are reflected from a crystal set at a shallow angle as a means of selecting those of a certain energy range. The neutrons are then allowed to pass through a second crystal mounted on a turntable. This crystal diffracts the neutrons in certain preferential directions; when it is turned, the counter at the bottom will detect the number of neutrons diffracted in each direction. In this way the experimenter can measure the interaction between the neutrons and the atoms in the crystal.

Laboratory. It is a solid disk traversed by a few narrow slits through which neutrons can pass. When the disk is whirled very rapidly it acts as a shutter for the beam, allowing short bursts of neutrons to pass each time a slit swings into the proper position. At full speed the chopper yields 1,000 pulses per second, each lasting a millionth of a second. The slits are an inch high by .01 inch wide. The extremely narrow beam that they produce makes it possible to work with small samples of material, as little as a hundredth of a gram. This means that we can experiment with separated isotopes, which are available only in fractions of a gram.

To detect the neutrons we use a crystal that scintillates when they strike it. The crystal is set up about 100 feet from the chopper. As each burst of neutrons traverses the long path, it becomes elongated in the direction of motion, the fast particles heading the parade and the slow ones bringing up the rear. Attached to the scintillating crystal are 100 separate counters, each turned on for successive intervals lasting a hundredth of the total flight time. A beam of light, which passes through the slits with each burst of neutrons, triggers the counting sequence, starting the first counter just in time to pick up the first neutrons. Thus each counter records particles in a very narrow range of speed. To record an absorption spectrum the counters are read first with an unobstructed neutron beam. Then a sample of material is placed between the chopper and detector and the counters read again. The silver spectra reproduced on page 6 show how much sharper resolution we get with the Brookhaven chopper than with earlier methods of selecting neutron velocities.

THE fast chopper works well with neutrons of about 10,000 to 10 electron volts. At the lower end of the resonance range, from 10 to .01 electron volt, the neutron waves are long enough for us to take advantage of their optical properties. These waves are about as long as the distance between atoms in crystal lattices and are diffracted by crystals just as X-rays are. The angle at which they are scattered in a given crystal depends on their wavelength, so that these neutrons can actually be separated according to speed in a crystal "monochromator."

Having obtained a beam of single-energy neutrons, we generally use it to study other crystals. X-rays, of course, have been used in the same way for half a century, but neutrons can do things that X-rays cannot. Neutron diffraction has opened an entirely new field in crystal analysis—the investigation of magnetic structure.

Every neutron is a tiny magnet. When it is scattered by magnetized atoms its deflection depends not only on the "grating spacing" of the crystal lattice but also on the magnetic forces. Neutron diffraction patterns are, therefore, different from X-ray patterns for magnetic substances, and from the difference we can read the magnetic configuration of the crystal.

At several laboratories neutron diffraction has been applied to the study of anti-ferromagnetic materials. In a ferromagnetic substance such as iron each atom is a magnet and all the atoms are lined up with their north poles facing in the same direction. Anti-ferromagnets also have magnetized atoms, but show no over-all magnetism. This has been explained by assuming that the individual atoms are aligned, but with their north poles pointing alternately in opposite directions. There was no way of checking this assumption, however, until C. G. Shull and J. S. Smart of the Oak Ridge National Laboratory tried neutron diffraction. They exposed a manganese oxide crystal to a monochromatic beam of neutrons. If the atoms are actually arranged according to the theory, a neutron will be attracted by one, repelled by the next, attracted by the third and so on. Because of this alternate attraction and repulsion the "unit cell"—the fundamental structural unit of the crystal—is twice as large when viewed by neutrons as by X-rays. The diffraction pattern should then contain neutrons at positions where there would be no energy in an X-ray pattern. Neutrons were found in the diffraction pattern in just these expected positions, but only when the crystal was kept at very low temperature. At room temperature the pattern disappeared, showing that the rigid anti-parallel alignment of the atoms no longer held good. Other anti-ferromagnetic substances are believed to have much more complicated magnetic structure than the simple scheme of manganese oxide. Knowing how their atomic magnets are arranged is important both for our basic understanding of the solid state and for a number of potentially useful applications. With neutron diffraction we can now find out.

BELOW the resonance range are the slowest neutrons, the thermals. They have this name because, by repeated collisions with carbon nuclei in the reactor, they have been slowed to speeds equal to, and even less than, the average vibrational speeds of the graphite molecules. These neutrons have energies from .01 to .0001 electron volt. At their slowest they travel only about 600 feet per second, corresponding to a temperature of only two degrees centigrade above absolute zero.

We have various ways to sort out thermal neutrons of different speeds. One of these is a slow chopper, which operates in the same way as the fast chopper. Another is the "spiral monochromator," an elaboration of the chopper idea that actually filters particles of a single speed out of the beam. It is made of a series of slotted disks on a single shaft, the position of the slots being adjustable (*see diagram on page 5*]. The disks are set so that each successive slot stands at a fixed angle to the one before it, or, in other words, so that the open path through the array of disks is a spiral. When the apparatus is rotated, a particle entering the first slot at the right speed will find each following slot moving into position just in time to let it through. Particles at other speeds will bump into the solid disks. By adjusting the angle between the slots or the speed of rotation of the shaft we can pick out neutrons of any desired speed.

Very slow neutrons are particularly useful for studying the motions of atoms in crystals. Moving in the same speed range as the particles they bump into, the neutrons can gain or lose a large proportion of their energy in collisions. From the energies of the scattered neutrons we can infer the motions of the atoms in the crystal lattice.

THE WAVELENGTHS of thermal neutrons are so long that it becomes just possible to reflect them with mirrors. Mirror reflection requires a smooth surface, and smoothness is a relative matter which depends upon the wavelength involved. The longest neutron waves are still 1,000 times shorter than waves of visible light, so that an "optically smooth" surface still looks very rough to a neutron. But just as a highway can reflect light that strikes it at a grazing angle, so a mirror that is rough to neutrons can reflect them when they strike at an exceedingly small angle, about a tenth of a degree.

Neutron mirrors are an effective means of measuring nuclear forces. This is because the force between the neutron and the atomic nuclei of mirror materials determines the maximum glancing angle at which reflection is possible. We can measure this "critical angle" quite precisely, and so calculate the nuclear force accurately. The method can be applied to a variety of atoms, since many materials make suitable mirrors. We have used highly polished solids, such as iron, nickel and beryllium; liquids, such as mercury, water and benzene, whose surfaces are sufficiently flat when quiet; gases, such as helium and nitrogen, contained in vessels with polished walls.

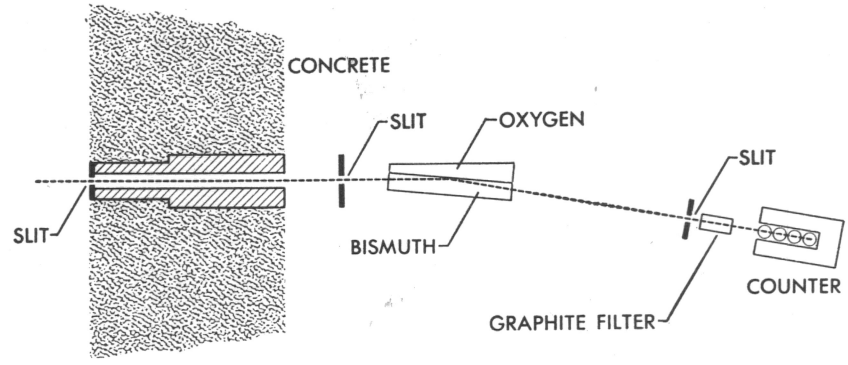
RECENTLY neutron mirrors have given us an accurate measurement of one of the smallest of all interactions between fundamental particles, the one between the neutron and the electron. It might seem at first that the force between these two fundamental particles should be zero, for the neutron has no

charge. According to modern meson theory, however, the neutron spends part of its life in a dissociated form, split into a proton surrounded by a cloud of mesons. It is still electrically neutral when seen from outside the meson cloud, because the negative charge of the mesons just balances the positive charge of the proton. But inside the cloud, which extends about 10^{-13} centimeter from the proton, there is an electric field. An electron inside the meson cloud should be attracted to the proton with a minute but measurable force.

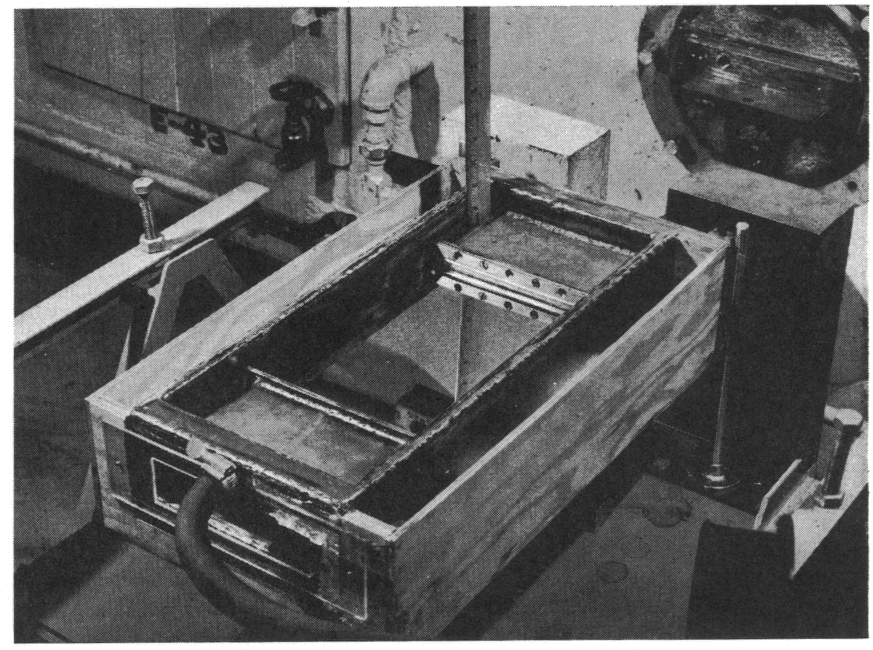
When we try to measure this force, however, we run into a major difficulty. The neutron-electron interaction is about 10,000 times weaker than that between the neutron and the atomic nucleus. It is impossible to study the interaction of neutrons with isolated electrons, and so the force we are after is always masked by one very much greater. To sidestep the large nuclear force the writer and his colleagues at Brookhaven, J. A. Harvey, M. D. Goldberg and Marilyn J. Stafne, devised a special neutron mirror. A block of bismuth was polished on one side and fitted into a tank so that a layer of liquid oxygen could be placed in contact with the polished surface. The neutrons were reflected from the boundary between the two materials. It happens that oxygen and bismuth have almost exactly the same nuclear interaction with neutrons, so the nuclear scattering balances for the two. The electron scattering, however, is quite different on opposite sides of the dividing boundary because each bismuth atom has 83 electrons and each oxygen atom only eight. So far as the neutrons are concerned the experiment is essentially the same as if they were reflected from a mirror made of electrons alone. The critical angle for the mirror thus gives the strength of the neutron-electron interaction directly.

The measured force turns out to be much smaller than predicted by the meson theory; in fact, it can be completely accounted for by a small magnetic interaction between the neutron and electron that does not involve the meson cloud at all. This means that there is some error in the present simple idea that neutrons exist transiently as protons and mesons. It may be that the proton itself, instead of being a point particle, is spread out to such an extent that its more distant parts act weakly on the electron; it may be that the splitting produces both positive and negative mesons, which cancel the electrical effect. To answer these questions fully we will have to design still subtler experiments as well as perhaps construct better theories of fundamental particles.

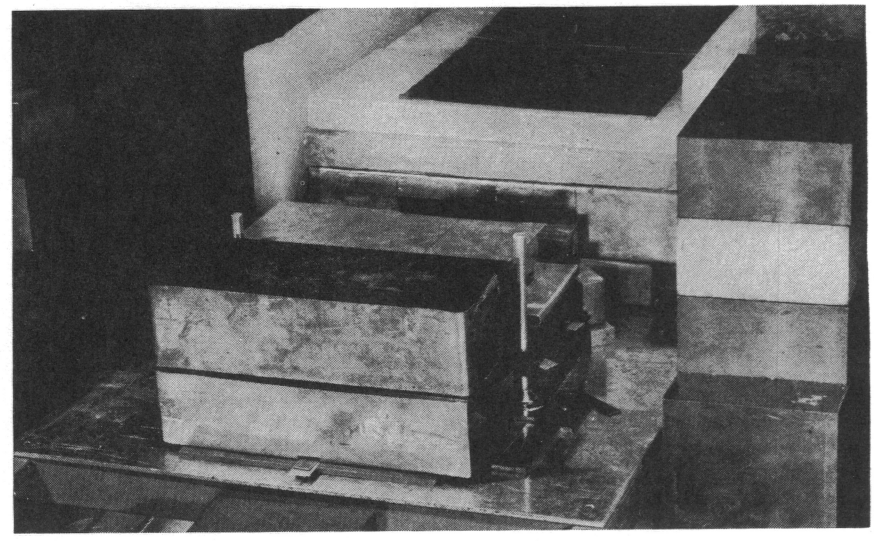
One thing seems certain. As more research reactors are built, and with higher neutron fluxes, their neutrons will play an increasingly important role in the search for the secrets of matter.



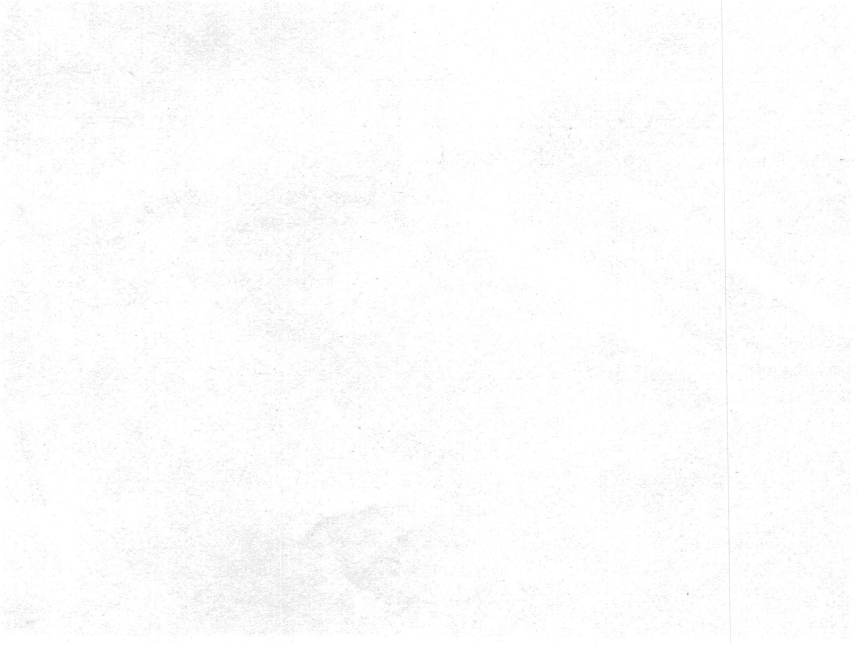
NEUTRON MIRROR experiments at Brookhaven utilized the arrangement shown in this side view. The neutrons emerged from the pile at the left and were reflected from the boundary between bismuth and liquid oxygen.



BISMUTH MIRROR is used in the arrangement depicted in the diagram above. During an experiment liquid oxygen is poured into the container around it. The neutrons emerge from the pile hole through the slit at right.



CADMIUM BLOCKS form a slit between the bismuth-oxygen mirror and the counter which detects neutrons reflected from it. The cadmium absorbs stray neutrons, as do the paraffin blocks that are seen in the background.



The Author

DONALD J. HUGHES has been working with atomic piles since the first one went into operation in a University of Chicago squash court. He was born in Chicago in 1915 and educated at the University of Chicago, receiving his Ph.D. in physics in 1940. Until early in 1943 Hughes worked at the Naval Ordnance Laboratory on mine and torpedo detectors. Then he transferred to the Manhattan District in Chicago and has been working in the field of nuclear physics ever since. He did research on pile neutrons first in Chicago with the original pile and later at the Hanford Engineer Works when the big plutonium-producing reactors were built. After the war he joined the Argonne National Laboratory as director of its nuclear physics division. In 1949 Hughes went to the Brookhaven National Laboratory, where he is now.

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